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Mathematical modelling of surface roughness in hard turning for evaluating the effects of process and tool parameters

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ABSTRACT
The work presented in this paper examines the effects of cutting parameters (cutting speed, feed rate and depth of cut) and tool parameters (nose radius and rake angle) onto the surface roughness through the mathematical model while machining AISI 52100 steel. Each parameter was set at three levels. A central composite face centred design (CCF) was employed to conduct the experiments. One of the most important data mining techniques, linear regression analysis, is applied in developing the empirical model. The effects of process and tool parameters have been studied with the help of response graphs, interaction graphs and mathematical model. Confirmation tests were conducted to verify the predictability of the model.

Keywords: Hard turning, surface roughness, central composite design, regression.

1. INTRODUCTION

The quality of machined surface becomes more critical in view of very high demand for performance, safety, lifetime, life cycle costs and reliability. The engineered components that are used in automotive, aerospace and other industries were applied in high stress and temperature surrounding. Hence, the surface roughness requirement of machined components become more important because it will cause sudden fatigue failure, therefore further research and development on machined surface of hard steel components are highly required. Hard turning is a process, in which materials in the hardened state are machined with the single point cutting tools. Since a large number of operations are required to produce the finished product, if some of the operations can be combined, or eliminated, or can be substituted by new process, product cycle time can be reduced and productivity can be improved. The traditional method of machining the hardened materials includes rough turning, heat treatment, and then grinding process. Hard turning eliminates the series of operations required to produce the component and thereby reducing the cycle time and hence resulting in productivity improvement. The performance of hard turning is measured in terms of surface finish, cutting forces, power consumed and tool wear. Surface roughness plays an important role as it influences the fatigue strength, wear rate, coefficient of friction, and corrosion resistance of machined components. Surface finish in hard turning, has been found to be influenced by a number of factors such as cutting speed, feed rate, work material characteristics, work hardness, tool nose radius tool geometry, stability of the machine tool the work piece set-up, and the use of cutting fluids, etc.

Various researchers have developed the surface roughness productive models for the conventional turning but those models may not be useful for hard turning because hard turning differs from that of the conventional turning process. Konig et al. [1] have reported that CBN and ceramic cutting tools are widely used in industries for the machining of the various hard materials. Thiele and Melkote [2] have investigated the cutting edge geometry and the work piece hardness on surface generation in the finish hard turning of AISI 52100 steel. Dahlman et al. [3] have conducted the study on the influence of rake angle, cutting speed and cutting depth on residual stresses in hard turning. M.Y. Noordin et al. [4] have described the performance of a multilayer tungsten carbide tool using response surface methodology (RSM) when turning AISI 1045 steel. Anderson et al. [5] have presented an alternative hybrid approach, combining response surface methodology (RSM) and principal component analysis (PCA) to optimize multiple correlated responses in a turning process. Gupta et al. [6] optimized machining parameters (cutting speed, feed rate, depth of cut, nose radius and cutting environment) with considerations of multiple performance measures (surface roughness, tool life, cutting force and power consumption) by applying Taguchi-fuzzy multi output optimization (MOO) in high speed CNC turning of AISI P-20 tool steel. Ilhan Asilturk and Mehmet Cunkas [7] have measured surface roughness during turning at different cutting parameters, artificial neural networks (ANN) and multiple regression approaches are used to model the surface roughness of AISI 1040 steel. Bicek et al. [8] have presented the results of turning hardened and normalized bearing steel AISI 52100 (DIN 100Cr6), comparing conventional fluid and dry with cryogenic machining. Aouici et al [9] have experimentally investigated the effects of cutting speed, feed rate, work piece hardness and depth of cut on surface roughness and cutting force components in hard turning. Suha Karim Shihaba et al. [10] have presented an overview of the past research hard turning using hard turning tools such as PCBN, cubic boron nitride, Ceramics, Carbide, etc. Major hard turning cutting materials and effect of hard turning process parameters on cutting forces, heat generation during cutting, surface finish and surface integrity, and tool wear have been discussed in light of the findings of the past research. From the literature, it can be observed that most of the works are conducted to study the effects of cutting speed, feed and depth of cut on various responses. In this work, the tool parameters namely nose radius and rake angle along with cutting speed, feed and depth of cut are considered to study their effects on the surface roughness in hard turning of AISI 52100 steel.

2. EXPERIMENTAL DESIGN

The cutting experiments were carried out on an engine lathe. In this investigation, for the work piece material, AISI 52100 steel was used. This material was chosen based on its wide applications in dies and moulds, roller and ball bearings, balls for shot peening, blasting, and barrel cleaning. The work pieces of 300mm length and 65mm diameter were considered for conducting experimentation. These bars were centered and cleaned by removing a 2mm depth of cut from the outside surface prior to the actual machining process. Surface finish of the work piece material was measured by Talysurf with 0.8 mm cut-off value. The surface roughness was measured at three equally spaced locations around the circumference of the work pieces to obtain the statistically significant data for each test. The surface roughness measurement given in this study is the mathematical average of the three readings taken from the work piece. Design of experimental technique was used for execution of the plan of experiments for five variables at three levels where by the levels are the values taken by the factors. The factors to be studied and the level of each factor are given in Table 1. Experiments are conducted as per central composite face centred [11] design. For five factors, the CCF design consist of 27 runs, which includes a 2^{5-1} (16) fractional factorial portion, 10 axial points and a central point. The experimental design along with response (surface roughness) is shown in Table 2.

Table 1 Machining parameters and their levels

Factor symbol	Factor	Level '-1'	Level '0'	Level '+1'
v	Cutting speed (m/min)	60	75	90
f	Feed (mm/rev)	0.052	0.078	0.104
d	Depth of cut (mm)	0.2	0.4	0.6
r	Nose radius(mm)	4	8	12
α	Rake angle(degrees)	0	6	12

Table 2 Experimental layout: CCF (5) design

S.No.	v	f	d	r	α	SR
1	-1[60]	-1[0.052]	-1[0.2]	-1[4]	+1[12]	4.49
2	-1[60]	-1[0.052]	-1[0.2]	+1[12]	-1[0]	1.84
3	-1[60]	-1[0.052]	+1[0.6]	-1[4]	-1[0]	3.74
4	-1[60]	-1[0.052]	+1[0.6]	+1[12]	+1[12]	1.33
5	-1[60]	+1[0.104]	-1[0.2]	-1[4]	-1[0]	5.10
6	-1[60]	+1[0.104]	-1[0.2]	+1[12]	+1[12]	3.36
7	-1[60]	+1[0.104]	+1[0.6]	-1[4]	+1[12]	7.50
8	-1[60]	+1[0.104]	+1[0.6]	+1[12]	-1[0]	3.80
9	+1[90]	-1[0.052]	-1[0.2]	-1[4]	-1[0]	2.87
10	+1[90]	-1[0.052]	-1[0.2]	+1[12]	+1[12]	2.76
11	+1[90]	-1[0.052]	+1[0.6]	-1[4]	+1[12]	1.11
12	+1[90]	-1[0.052]	+1[0.6]	+1[12]	-1[0]	3.93
13	+1[90]	+1[0.104]	-1[0.2]	-1[4]	+1[12]	1.87
14	+1[90]	+1[0.104]	-1[0.2]	+1[12]	-1[0]	4.50
15	+1[90]	+1[0.104]	+1[0.6]	-1[4]	-1[0]	2.02
16	+1[90]	+1[0.104]	+1[0.6]	+1[12]	+1[12]	3.41
17	-1[60]	0[0.078]	0[0.4]	0[8]	0[6]	3.85
18	+1[90]	0[0.078]	0[0.4]	0[8]	0[6]	2.81
19	0[75]	-1[0.052]	0[0.4]	0[8]	0[6]	2.86
20	0[75]	+1[0.104]	0[0.4]	0[8]	0[6]	5.56
21	0[75]	0[0.078]	-1[0.2]	0[8]	0[6]	3.42
22	0[75]	0[0.078]	+1[0.6]	0[8]	0[6]	3.33
23	0[75]	0[0.078]	0[0.4]	-1[4]	0[6]	3.75
24	0[75]	0[0.078]	0[0.4]	+1[12]	0[6]	3.20
25	0[75]	0[0.078]	0[0.4]	0[8]	-1[0]	3.90
26	0[75]	0[0.078]	0[0.4]	0[8]	+1[12]	3.53
27	0[75]	0[0.078]	0[0.4]	0[8]	0[6]	3.33

3. DATA ANALYSIS AND DISCUSSION OF RESULTS

The analysis of experiments was made into two phases. The first one concerned the analysis of factor and interaction effects. Model for surface roughness has been developed in second phase.

3.1. Analysis of the factors and interactions

From the factorial portion of CCF design, both factor and interaction effects (at two levels) can be obtained. It can be observed from axial and central portion of CCF design, considering experiments from 17 to 27, factor effects (at three levels) of each factor can be obtained when all other factors are at 0 levels. Using the experimental data, level means have been calculated. The level means obtained from factorial portion of CCF design, axial portion of CCF design for surface roughness is given in Tables 3 & 4. The influence of each control factor can be more clearly presented in response graphs given in Figures 1 & 2.

Table 3 Average Response of surface roughness for Factorial Portion of CCF Design

	v	F	d	r	α
Level -1	3.895	2.759	3.349	3.587	3.475
Level +1	2.809	3.945	3.355	3.116	3.229

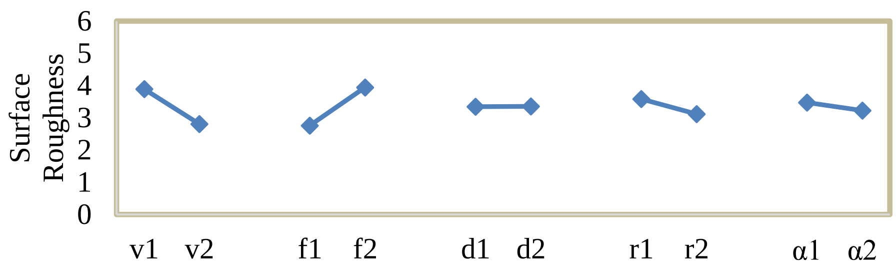

Figure 1 Response Plot of Surface Roughness for Factorial Portion of CCF Design

Table 4 Average Response of Surface Roughness for One Factor at a Time Analysis

	v	f	d	r	α
Level -1	3.85	2.86	3.42	3.75	3.90
Level 0	3.33	3.33	3.33	3.33	3.33
Level +1	2.81	5.56	3.33	3.20	3.53

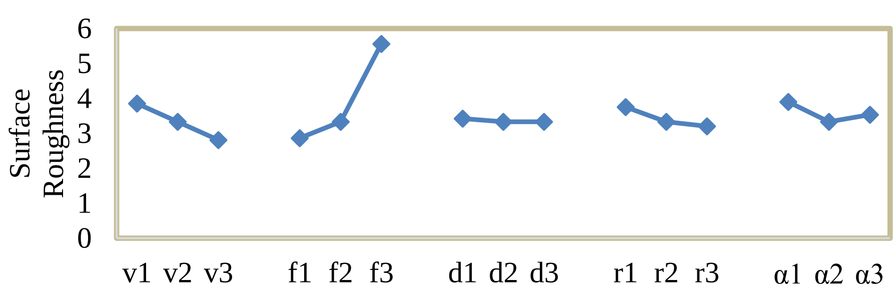

Figure 2 Response Plot of Surface Roughness for One Factor at a Time Analysis

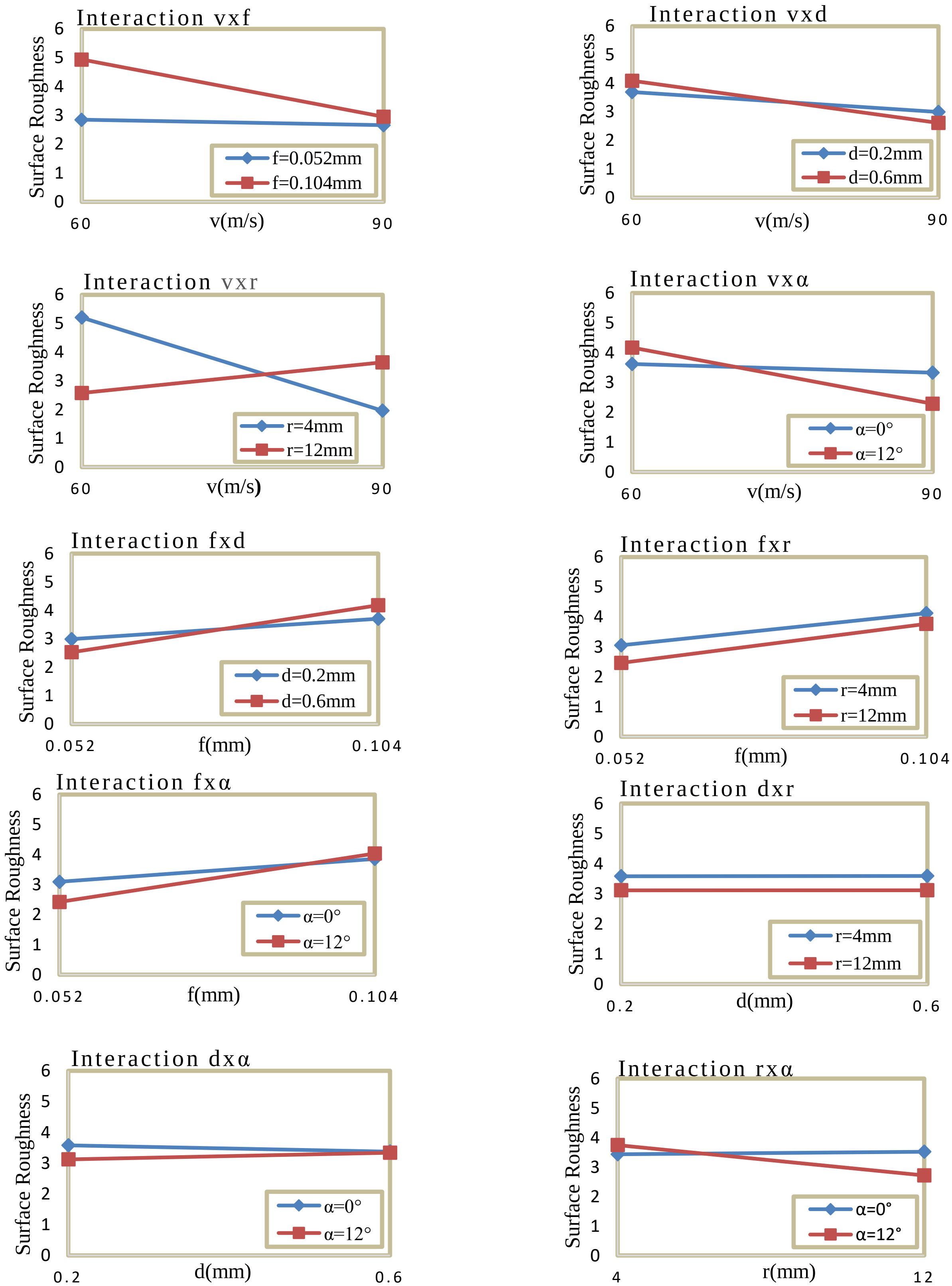

Figure 3 Interaction Graphs of Parameters for surface roughness

Table 5 Interaction Matrices for the surface roughness

vxf	f1	f2	vxd	d1	d2
v1	2.85	4.94	v1	3.6975	4.0925
v2	2.6675	2.95	v2	3.00	2.6175
vxr	r1	r2	vxα	α1	α2
v1	5.2075	2.5825	v1	3.62	4.17
v2	1.9675	3.65	v2	3.33	2.2875
fxd	d1	d2	fxr	r1	r2
f1	2.99	2.5275	f1	3.0525	2.465
f2	3.7075	4.1825	f2	4.1225	3.7675
fxα	α1	α2	dxr	r1	r2
f1	3.095	2.4225	d1	3.5825	3.115
f2	3.855	4.035	d2	3.5925	3.1175
dxα	α1	α2	rxα	α1	α2
d1	3.5775	3.12	r1	3.4325	3.7425
d2	3.3725	3.3375	r2	3.5175	2.715

The analysis of the interactions gives the additional information about the process. Interaction effects can be obtained by calculating all combinations of control factors. The interaction matrix enables the construction of interaction graphs, which indicate the existence or non-existence of interaction between two control factors. If the lines in the interaction graph are parallel, it indicates non-existence of interaction. The interaction matrix and interaction graphs for surface roughness are shown in Table 5 and Figure 3.

3.2. Model for surface roughness

Central composite designs are best for fitting a second order model, and accordingly CCF data is used to fit a second order model. The input data to SPSS software is provided in coded form of factors i.e. -1 to +1. To be precise, value of the factor in coded scale is = (actual value of factor – central value in the range) / (difference between the maximum value and central value in the range). Applying backward linear regression, which eliminates the insignificant factors one at a time, option of SPSS is used to develop the surface roughness (SR) model.

$$SR= 3.653- 0.541v + 0.677\ f – 0.24\ r -0.304\ v^2 – 0.452\ vf -0.194\ vd + 1.077\ vr – 0.398\ v\alpha + 0.234\ fd + 0.213\ f\alpha – 0.278\ r\alpha$$

(R-square value= 0.945)

The R-square value of 0.945 indicated that 94.5% of the variability in surface roughness was explained by the model. The feed rate, cutting speed, and nose radius has significant effect on surface roughness. The square term of cutting speed also enter into the model which indicates the non-linearity of response. The interaction between various parameters indicates the behaviour of response at different levels of these factors. Conducting confirmation experiments has been the final step of the design of experimental (DOE) process. The confirmation is performed by conducting tests using combinations of the factors and levels that are not previously evaluated. It can be observed that the error percentage associated with the model is within the limits. Therefore, we can consider the empirical model which correlates the surface roughness with the process and tool parameters, with a reasonable degree of approximation within the given working conditions.

4. CONCLUSIONS

In this work, empirical model for surface roughness has been developed in terms of process and tool parameters. The central composite face centered design was used to conduct experiments. The following observations were made from this work:

1. From the model equation, it can be observed that the factors cutting speed, feed rate and nose radius are affecting individually. The factors depth of cut and rake angle have no significant effect on surface roughness, but its interaction with other parameters has significant effect on surface roughness.

2. The surface roughness increases with increase in feed and decreases with increase in cutting speed and nose radius which is coinciding with the established theory.
3. The feed is observed to be most dominant factor followed by cutting speed and nose radius on surface roughness within the ranges considered.
4. The significance of second order effects and the two way interactions amongst the process and tool parameters were identified.
5. By explicit incorporation of the square and interaction terms, the CCF design model gives better insight into the process. So, CCF design model developed for cutting speed serves as a good alternative to the popular multiplicative model.

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